

Full Counting Statistics with Spin-sensitive Detectors reveals Spin-singlets

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We study the full counting statistics of electric current to several drain terminals with spin-dependent entrance conductances. We show that the statistics of charge transfers can be interpreted in terms of single electrons and spin-singlet pairs coming from the source. If the source contains transport channels of high transparency, a significant fraction of electrons comes in spin-singlet pairs.

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Spin-singlet pairs are of a fundamental interest, since they provide a generic example of an entangled state [1, 2]. The entanglement presents a fundamental difference between classical and quantum mechanics, and this has been unambiguously defined and quantified in form of theorems involving spin-singlets [3]. The modern developments in quantum information and manipulation have increased the interest in experimental demonstration of entanglement. While quantum optics presents significant experimental advances in this direction [4], the unambiguous experimental illustration of electron entanglement in solid state is still to be realized.

In recent years, a significant number of publications propose such experiment in various solid-state nanostructures. In these proposals, most attention is paid to production and subsequent detection of spin-singlet pairs of electrons. A superconductor seems to be a natural source of spin-singlet pairs, and different schemes involving a superconductor and normal leads have been considered: two dots [5], two Luttinger liquids [6], two carbon nanotubes [7], or just two normal leads [8]. It was suggested that exchange interaction can be used to produce singlets in a triple quantum dot device [9] and a 2D electron gas with four point contacts [10]. More recently, it was realized that normal leads are a source of spin-entangled electrons [11]. The current noise was proposed to detect spin [12, 13, 14, 15] and orbital [16] entanglement. In Refs. [17] the full counting statistics (FCS) approach [18] was used to reveal the violation of a Clauser-Horne inequality in multiterminal devices. Charge current noise has been recently studied in systems combining ferromagnets and normal metals [19]. FCS of spin currents in a two-terminal device has been addressed in [20].

In this Letter, we consider an almost traditional method of spin detection that relies on spin sensitivity of the conductance of a normal metal-ferromagnet interface [21]. We demonstrate that one does not have to do anything special to *produce* spin-singlets: they are readily present in almost any flow of degenerate electrons, and the FCS of currents in spin-sensitive drains reveals this circumstance. We do not consider any other type of entanglement than that of a spin-singlet pair. We

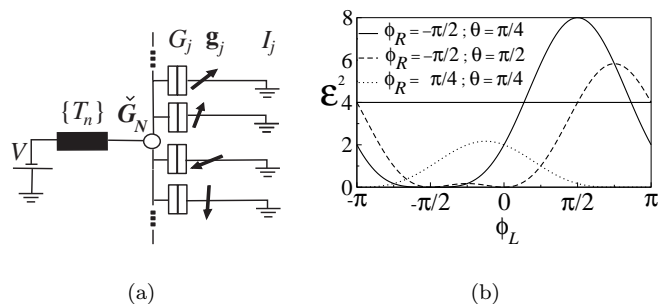


FIG. 1: (a) The setup considered. The coherent conductor (black rectangular) is a source of electrons being transferred to the drains: spin-sensitive tunnel junctions. The probabilities of one- and two-electron transfers are extracted from measurement of the currents I_j in the drains and their correlators. (b) The square of Bell's parameter for the setup described in the text plotted versus the switching angle $\phi_L \equiv \arccos \mathbf{n}_L \cdot \mathbf{n}'_L$ for several values of $\phi_R \equiv \arccos \mathbf{n}_R \cdot \mathbf{n}'_R$ and $\theta \equiv \arccos \mathbf{n}_L \cdot \mathbf{n}_R$ when all vectors are coplanar. The values of \mathcal{E}^2 above the horizontal line violate Bell's inequality.

consider a generic coherent conductor characterized by a set of transmission eigenvalues T_n . The conductor is assumed to be short enough for no spin-scattering taking place while an electron traverses the conductor, so that each transport channel n is spin-degenerate. The fraction of electrons coming in spin-singlet pairs is eventually $\sum_n T_n^2 / \sum_n T_n$, $2/3$ for a diffusive conductor.

To see that a significant part of electrons comes in spin-singlets, we concentrate on a multi-terminal setup (Fig. 1(a)), which consists of a coherent conductor representing the source of electrons and several drains, the conductances of which depends on spin. The simplest way to achieve this is to connect ferromagnetic leads to a normal metallic island [21, 22]. Spin-sensitive conductance can also be realized with semiconductor quantum dots in a magnetic field [23]. In our proposal, the drains are to detect the electron propagation via the coherent conductor. They thus should not disturb much the electron flow. This is ensured by the total conductance G_d of the drains being much bigger than the conductance

of the “source”. This is easy to realize if there are many transport channels opening to the drains, i.e. $G_d \gg e^2/\hbar$, which we assume. The electron spin should not change when the electrons propagate from the “source” to the drains, which implies that the size of the normal island should not exceed the spin relaxation length. We will study zero-frequency (cross) cumulants of electric current in the drains: the FCS of electron transfers.

The advantage of the FCS approach to quantum transport is that it not only gives numerical values of various cumulants of the charge transferred, but also allows to identify elementary independent events of transfer. Elementary events are defined as follows: the generating function (defined in Eq. (1) below) can be presented as $S \propto \sum_n \ln Z_{el}(n)$, $Z_{el}(n)$ being a polynomial in $X_j := \exp i\chi_j$. This implies that the FCS can be interpreted as composition of elementary events characterized by the generating function $Z_{el}(n)$. If the coefficients of $X_1^{m_1} \dots X_j^{m_j} \dots$ are real and positive, they can be interpreted as probabilities that m_j electrons were transmitted through channel n to terminal j in the course of the elementary event. This facilitates the interpretation and understanding of quantum transport. The FCS indeed reveals the many-body aspect of transport. In principle one may have elementary events involving many particles. Ref. [18] shows that for two-terminal nonferromagnetic devices elementary events involve only one electron.

It is convenient to work with the generating function of FCS defined in such a way that the probability $P_\tau(N)$ to transfer N electrons during a time interval τ reads

$$P_\tau(N) = \int \frac{d\chi}{2\pi} \exp(S(\chi) - i\chi N). \quad (1)$$

For a coherent conductor biased at voltage $eV \gg k_B T$, the cumulant generating function (CGF) is given by [18]

$$S(\chi) = \frac{eV\tau}{\pi\hbar} \sum_n \ln(R_n + T_n \exp(i\chi)) , (R_n \equiv 1 - T_n) .$$

Interpretation of this in terms of elementary events is as follows: In each transport channel n , electrons make $eV\tau/\pi\hbar$ independent attempts to traverse the conductor. An attempt is successful with probability T_n . Let us generalize this to our setup assuming at the moment that the conductances of the drains are *not* spin-sensitive. To account for electron transfers to each drain j , we introduce multiple counting fields χ_j . The CGF reads

$$S(\{\chi_j\}) = \frac{eV\tau}{\pi\hbar} \sum_n \ln \left(R_n + T_n \sum_j p_j^{(0)} e^{i\chi_j} \right) . \quad (2)$$

This also allows for evident interpretation: after a successful attempt to traverse the conductor, the electron gets to the drain j with probability $p_j^{(0)}$. These probabilities are nothing but the normalized conductances of the drains, $p_j^{(0)} = G_j / \sum_k G_k$, so that $\sum_j p_j^{(0)} = 1$.

Now we are ready to formulate the main quantitative result of our work. If the conductances of the drains are spin-sensitive, the CGF reads

$$S = \frac{eV\tau}{2\pi\hbar} \sum_n \ln \left[R_n^2 + 2R_n T_n \sum_j p_j e^{i\chi_j} + T_n^2 \sum_{j,k} p_{j,k} e^{i(\chi_j + \chi_k)} \right] . \quad (3)$$

The interpretation in terms of elementary events is as follows: The electrons in each transport channel make $eV\tau/2\pi\hbar$ independent attempts to traverse the conductor. The outcomes of each attempt are: a) with probability R_n^2 , no electron is transferred, b) with probability $2R_n T_n$, one electron traverses the conductor, c) with probability T_n^2 , two electrons make it. At the next stage, if one electron is transferred, it goes to the drain j with probability p_j . If two electrons are transferred, the probability to have one electron transferred to the drain j and another to the drain k equals $2p_{j,k} - \delta_{jk}p_{j,j}$. If the drains are not sensitive to spin, $p_{j,k} = p_j p_k$, and we recover Eq. (2). If they are, $p_{j,k} \neq p_j p_k$ in general. The concrete form of $p_{j,k}$ allows us to prove that if two electrons are transferred, they are transferred in *spin-singlet* state. We notice that elementary processes forming low-frequency FCS in multiterminal setups can, in principle, involve many particles [18]. The fact that in our specific setup an elementary event involves no more than two particles is a result of calculation and was not assumed apriori. Also, no expansion in the transmission values T_n was adopted to limit the elementary processes to two-electron ones, but the formulas are exact analytical expressions for the setup considered. We show that the two-electron process is a transfer of a spin-singlet pair, and this is the main result of our paper.

Let us give the concrete form for $p_{j,k}$. The spin-dependent conductance of each drain can be presented as $G_j(1 + \mathbf{g}_j \cdot \hat{\sigma})$, $\hat{\sigma}$ being a vector of Pauli matrices, and \mathbf{g}_j being parallel to the magnetization direction of the corresponding ferromagnet. The conductances for majority (minority) spins are thus $G_j(1 + |\mathbf{g}_j|)$ ($G_j(1 - |\mathbf{g}_j|)$). Since conductances must remain positive, $|\mathbf{g}_j| \leq 1$. The probabilities under consideration read

$$p_j = p_j^{(0)} \frac{1 - \bar{\mathbf{g}} \cdot \mathbf{g}_j}{1 - \bar{\mathbf{g}}^2} , \quad (4a)$$

$$p_{j,k} = p_j^{(0)} p_k^{(0)} \frac{1 - \mathbf{g}_j \cdot \mathbf{g}_k + (\bar{\mathbf{g}} \times \mathbf{g}_j) \cdot (\bar{\mathbf{g}} \times \mathbf{g}_k)}{1 - \bar{\mathbf{g}}^2} , \quad (4b)$$

where we introduced a weighted quantity $\bar{\mathbf{g}} \equiv \sum_j p_j^{(0)} \mathbf{g}_j$. Eqs. (3,4) determine the FCS in our setup and thus present the quantitative results of our work.

Before discussing the probabilities (4), their manifestation in the (cross)cumulants of the currents, and their

relation to spin-singlets, let us outline the derivation of Eqs. (3), and (4). Our starting points are the Green function theory for FCS and its circuit-theory extension to the multi-terminal case [24]. We extend this technique to spin-dependent conductances in the spirit of Ref. [22]. In this technique, one works with Keldysh Green functions that are 4×4 matrices in Keldysh and spin index.

The Green functions \check{G}_s in the source lead and \check{G}_j in the drain leads are fixed and determined by filling factor $f_s(\varepsilon)$, $f_j(\varepsilon)$ and counting field χ_j in the corresponding lead. They are scalars in spin space and read

$$\check{G}(\chi) = e^{i\tau_z \chi/2} \begin{pmatrix} 1 - 2f & -2f \\ -2(1 - f) & 2f - 1 \end{pmatrix} e^{-i\tau_z \chi/2},$$

τ_z being the diagonal Pauli matrix in Keldysh space. The Green function \check{G}_N in the node is determined from the balance of (spin-dependent) matrix currents via all the connectors [24]. For the source, the matrix current is [25]

$$\check{I}_s(\{\chi_\alpha\}) = \frac{e^2}{2\pi\hbar} \sum_n \frac{T_n [\check{G}_s, \check{G}_N]}{1 + T_n (\{\check{G}_s, \check{G}_N\} - 2)/4}. \quad (5)$$

where $\{\dots\}$ ($\{\dots\}$) denote (anti)commutator of two matrices. As to the matrix currents through spin-sensitive drains, they acquire spin structure. We assume that the normal metal-ferromagnet interfaces are tunnel junctions so that all transmission eigenvalues $\ll 1$: it is known that tunnel junctions provide the best spin sensitivity [21]. The current can be derived with Tunneling Hamiltonian method and reads

$$\check{I}_j = \frac{G_j}{2} [(1 + \mathbf{g}_j \cdot \hat{\boldsymbol{\sigma}}) \check{G}_j, \check{G}_N]. \quad (6)$$

This relation has been first derived in Ref. [26] in the superconducting context and is valid here owing to universality of matrix structure of \check{G} . Provided \check{G}_N is found, the CGF can be determined from the relation $\partial S / \partial \chi_j = (\tau / 8e^2) \int d\varepsilon \text{Tr} \{\tau_z \check{I}_j\}$. To determine \check{G}_N , one generally has to solve the current balance equation $\check{I}_s + \sum_j \check{I}_j = 0$, with the constraints $\check{G}_N^2 = 1$ and $\text{Tr} \check{G}_N = 0$. However, in the general case, the solution is complicated by multiple electron trips from the drains to the source and back. We do not wish to account for this, since in our setup the drains are merely detectors and are not supposed to perturb the electron flow. So we will solve this equation only in the corresponding limiting case $G_d \gg G_s$. This means that \check{G}_N is to be determined from the balance of the drain currents only, $\sum_j \check{I}_j = 0$. The source matrix current is found by substitution of the solution into Eq. (5). We consider only the shot noise limit $eV \gg k_B T$. In this case, the contribution to FCS comes from the energy strip of width eV where $f_s = 1$, $f_j = 0$. From current conservation, one proves that in this limit

$$S = \frac{eV}{2} \sum_n \text{Tr} \ln \left\{ 1 + \frac{T_n}{4} (\{\check{G}_s, \check{G}_N\} - 2) \right\}.$$

We have that the solution \check{G}_N reads

$$\check{G}_N = \begin{pmatrix} 1 & 0 \\ \beta_0 + \boldsymbol{\beta} \cdot \hat{\boldsymbol{\sigma}} & -1 \end{pmatrix},$$

with $\beta_0 = -2(p_\chi - \bar{\mathbf{g}} \cdot \mathbf{g}_\chi) / (1 - \bar{\mathbf{g}}^2)$, $\boldsymbol{\beta} = -2(\mathbf{g}_\chi - p_\chi \bar{\mathbf{g}} + \bar{\mathbf{g}} \times (\bar{\mathbf{g}} \times \mathbf{g}_\chi)) / (1 - \bar{\mathbf{g}}^2)$, $p_\chi \equiv \sum_j (G_j / G_d) e^{i\chi_j}$, and $\mathbf{g}_\chi \equiv \sum_j (G_j / G_d) e^{i\chi_j} \mathbf{g}_j$. Substituting the concrete expressions for the Green functions, we arrive at Eq. (3), with probabilities given by (4).

Now we are in the position to discuss and interpret the probabilities (4). Let us first consider the case $\bar{\mathbf{g}} = 0$. Although it is not the most general case, the conductances of the drains can be tuned to achieve this. The expressions for probabilities are simpler in this case:

$$p_j = p_j^{(0)}; \quad p_{j,k} = p_j^{(0)} p_k^{(0)} (1 - \mathbf{g}_j \cdot \mathbf{g}_k). \quad (7)$$

Thus, the one-electron probability to get into a certain drain does not depend on all other drains, except that it is determined by the normalized conductance of the drain. It is not sensitive to electron spin either. In contrast to this, the two-electron probability does depend on spin. The concrete expression for two-electron probability can be re-derived if one starts with the two-particle density matrix of the spin-singlet state

$$\hat{\rho}_{sing} = \frac{1}{4} (\hat{1} - \hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2), \quad (8)$$

1, 2 numbering the particles. For one particle, the probability to tunnel to a certain drain is proportional to $\text{Tr} \{G_j (1 + \mathbf{g}_j \cdot \hat{\boldsymbol{\sigma}}) \hat{\rho}\}$. Consequently, the probability for two particles to tunnel to the drains j and k is proportional to $\text{Tr} \{G_j G_k (1 + \mathbf{g}_j \cdot \hat{\boldsymbol{\sigma}}_1) (1 + \mathbf{g}_k \cdot \hat{\boldsymbol{\sigma}}_2) \hat{\rho}\} + (1 \leftrightarrow 2)$. Using the spin-singlet density matrix, we recover Eq. (7). This not only means that the electrons come with opposite spin, but also the probabilities distinguish between spin-singlet and a component of the triplet state with opposite spin.

Let us put these probabilities in the context of general discussion of the relations between locality and quantum entanglement that provide the initial fascination with the subject [1]. Let us assign classical observers, *Alice* and *Bob* to two of the drains. Let us also disregard the current fluctuations of the source and just let it pass a fixed number of electrons. The observers can change the direction of $\mathbf{g}_{A,B}$ in their own drains. If only one-electron processes occur, the readings of *Alice* and *Bob* would be uncorrelated. One can interpret this as locality: the counted electrons are independent, and an electron counted by *Alice* would never get to *Bob* passing information about direction of \mathbf{g}_A . However, if spin-singlets are coming, the readings do correlate by virtue of Eq. (7). If *Bob* knows the readings of *Alice*, he can compare it with his own observations and figure out the direction of her \mathbf{g}_A [27].

In the general case, $\bar{\mathbf{g}} \neq 0$, the probabilities are less straightforward to interpret. The one-electron probability for a given drain does depend on the \mathbf{g}_j of the other

drains by means of $\bar{\mathbf{g}}$. The reason for this is transparent: there is *spin accumulation* in the node [21, 22]. The $-\bar{\mathbf{g}}$ is the average polarization of electrons in the node. In fact, the one-electron probabilities can be re-derived assuming that one-particle density matrix reads $\hat{\rho} = (\hat{1} - \bar{\mathbf{g}} \cdot \hat{\boldsymbol{\sigma}})/2$. The two-particle density matrix reads

$$\hat{\rho} = \frac{1}{4} [\hat{1} - (1 - \bar{\mathbf{g}}^2) \hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2 - (\bar{\mathbf{g}} \cdot \hat{\boldsymbol{\sigma}}_1)(\bar{\mathbf{g}} \cdot \hat{\boldsymbol{\sigma}}_2)], \quad (9)$$

This density matrix is the mixture of the singlet density matrix and of the $(\hat{\boldsymbol{\sigma}}_1 + \hat{\boldsymbol{\sigma}}_2) \cdot \bar{\mathbf{g}} = 0$ component of the triplet density matrix, with respective weights $1 - \bar{\mathbf{g}}^2/2$ and $\bar{\mathbf{g}}^2/2$. We stress that Eq. (9) gives the density matrix of electrons that go to drains, and not the one of electrons coming from the source: They still come in spin-singlet pairs. Spin accumulation thus distorts this matrix, both for single electrons and electron pairs.

The elementary probabilities $p_j, p_{j,k}$ can be readily extracted from the measurement of average currents I_j and low-frequency noise (correlations) S_{jk} in the drains, since

$$I_j = I p_j, \quad (10a)$$

$$S_{jk} = 2eI [\Theta(p_{j,k} - 2p_j p_k) + p_j \delta_{j,k}], \quad (10b)$$

I being the current in the source, and $\Theta \equiv \sum_n T_n^2 / \sum_n T_n$ giving the fraction of electrons coming in spin-singlet pairs. Θ is related to the Fano factor F (ratio of noise to $2eI$) of the source, $\Theta = 1 - F$. We notice that, in contrast to optics, the measurement is not time resolved, since we access FCS at low frequency, at times much longer than time intervals between electron transfers.

The simplest illustration is a ballistic quantum point contact ($T_n = 1$) as source and two drains 1, 2 that can only accept electrons with spin up (1) and down (2). This implies that *all* electrons come in spin-singlet pairs and, since $g_1^z = -g_2^z = 1$, $p_1 = p_2 = 1/2$, $p_{11} = p_{22} = 0$, $p_{12} = 1/2$. Therefore the same amount of electrons go to the drains 1 and 2, and there is an absolute correlation of the currents in the drains, $S_{11} = S_{22} = S_{12} = 0$!

We demonstrate that our setup can be used to illustrate the violation of a Bell-Clauser-Horne-Shimony-Holt inequality [3]. We consider four drains. The drains 1, 2 and 3, 4 are pairwise antiparallel, i.e. $\mathbf{g}_1 = -\mathbf{g}_2 = \mathbf{g}_L$, $\mathbf{g}_3 = -\mathbf{g}_4 = \mathbf{g}_R$. For simplicity, $G_1 = G_2$ and $G_3 = G_4$.

This is a close analogue of the optical experiments [4]. Each pair of drains forms a “spin detector”: e.g. the current through drain 1 (2) measures the number of electrons coming with spin up (down) with respect to \mathbf{g}_L . The $|\mathbf{g}_{L,R}|$ turn out to be the detectors’ efficiencies. The measurements are performed with each polarization taking two directions, $\mathbf{n}_{L,R}, \mathbf{n}'_{L,R}$ ($\mathbf{n}_{L,R}^2 = \mathbf{n}'_{L,R}^2 = 1$). We shall discard the events where both electrons of a singlet go to the same detector by normalizing the probabilities to go to different detectors. For instance, the probability to measure spin up in the left and right detectors reads $P_{++} = p_{1,3}/(p_{1,3} + p_{1,4} + p_{2,3} + p_{2,4})$.

The Bell parameter is defined as $\mathcal{E} \equiv |E(\mathbf{n}_L, \mathbf{n}_R) + E(\mathbf{n}'_L, \mathbf{n}_R) + E(\mathbf{n}_L, \mathbf{n}'_R) - E(\mathbf{n}'_L, \mathbf{n}'_R)|$ where the correlator is given by $E(\mathbf{n}, \mathbf{n}') = P_{++} + P_{--} - P_{+-} - P_{-+}$. From Eq. (7) we obtain that $E = -\mathbf{g}_L \cdot \mathbf{g}_R$. The Bell parameter is proportional to efficiencies of both detectors, $\mathcal{E} = |\mathbf{g}_L| |\mathbf{g}_R| \mathcal{E}_0$, where $\mathcal{E}_0 = |\mathbf{n}_L \cdot \mathbf{n}_R + \mathbf{n}'_L \cdot \mathbf{n}_R + \mathbf{n}_L \cdot \mathbf{n}'_R - \mathbf{n}'_L \cdot \mathbf{n}'_R|$ is the expression for fully efficient detectors from the work of Bell. Since the maximum value of \mathcal{E}_0 is $2\sqrt{2}$, Bell’s inequality $\mathcal{E} \leq 2$ is violated at certain configurations of \mathbf{n} provided the polarization exceeds $2^{-1/4} \simeq 84\%$, in agreement with [15]. We plot \mathcal{E} in Fig. 1(b).

To conclude, we have shown that the low-frequency FCS of a coherent conductor can be interpreted in terms of single-electron and spin-singlet pairs transfers. This can be revealed and quantified by using spin-sensitive drains.

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